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Computational Fluid Dynamics of Choanoflagellate Filter-Feeding

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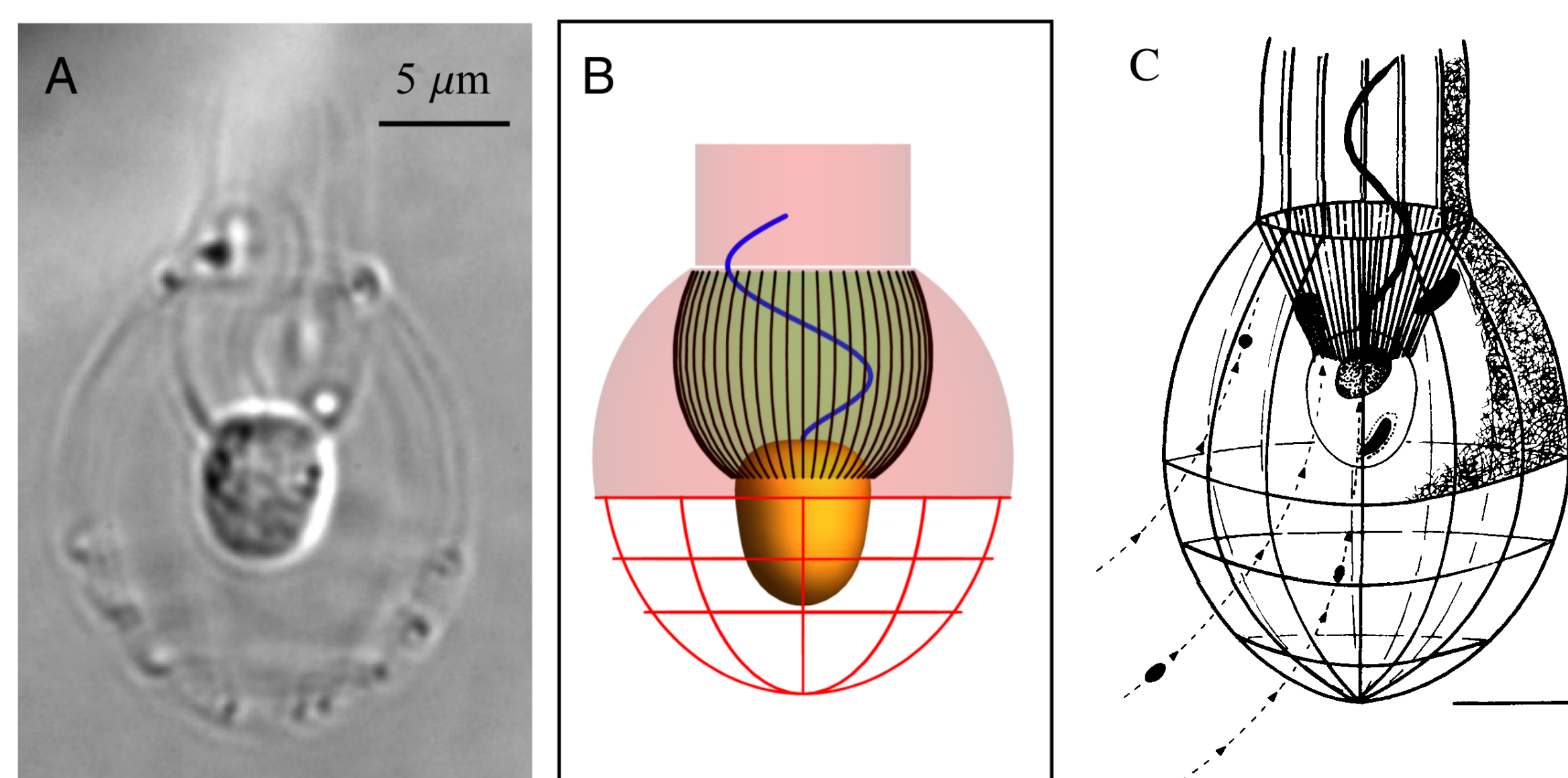
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Choanoflagellates are unicellular aquatic organisms with a single flagellum that drives a feeding current through a funnel-shaped collar filter on which bacteria-sized prey are caught. Using computational fluid dynamics (CFD) we model the beating flagellum and the complex filter flow of the choanoflagellate *Diaphanoeca grandis*. Our CFD simulations based on the current understanding of the morphology underestimate the experimentally observed clearance rate by more than an order of magnitude: The beating flagellum is simply unable to draw enough water through the fine filter. Our observations motivate us to suggest a radically different filtration mechanism that requires a flagellar vane (sheet), and addition of a wide vane in our CFD model allows us to correctly predict the observed clearance rate.

Morphology of Choanoflagellate *Diaphanoeca grandis*



Morphology of *Diaphanoeca grandis*. (A) Microscopic image of freely swimming choanoflagellate. (B) Model morphology with cell (orange), collar filter (green surface and black lines), flagellum (blue), and lorica (red) (C) By beating their flagellum, the choanoflagellates create a flow of water across the collar filter, and this collar filters out prey.

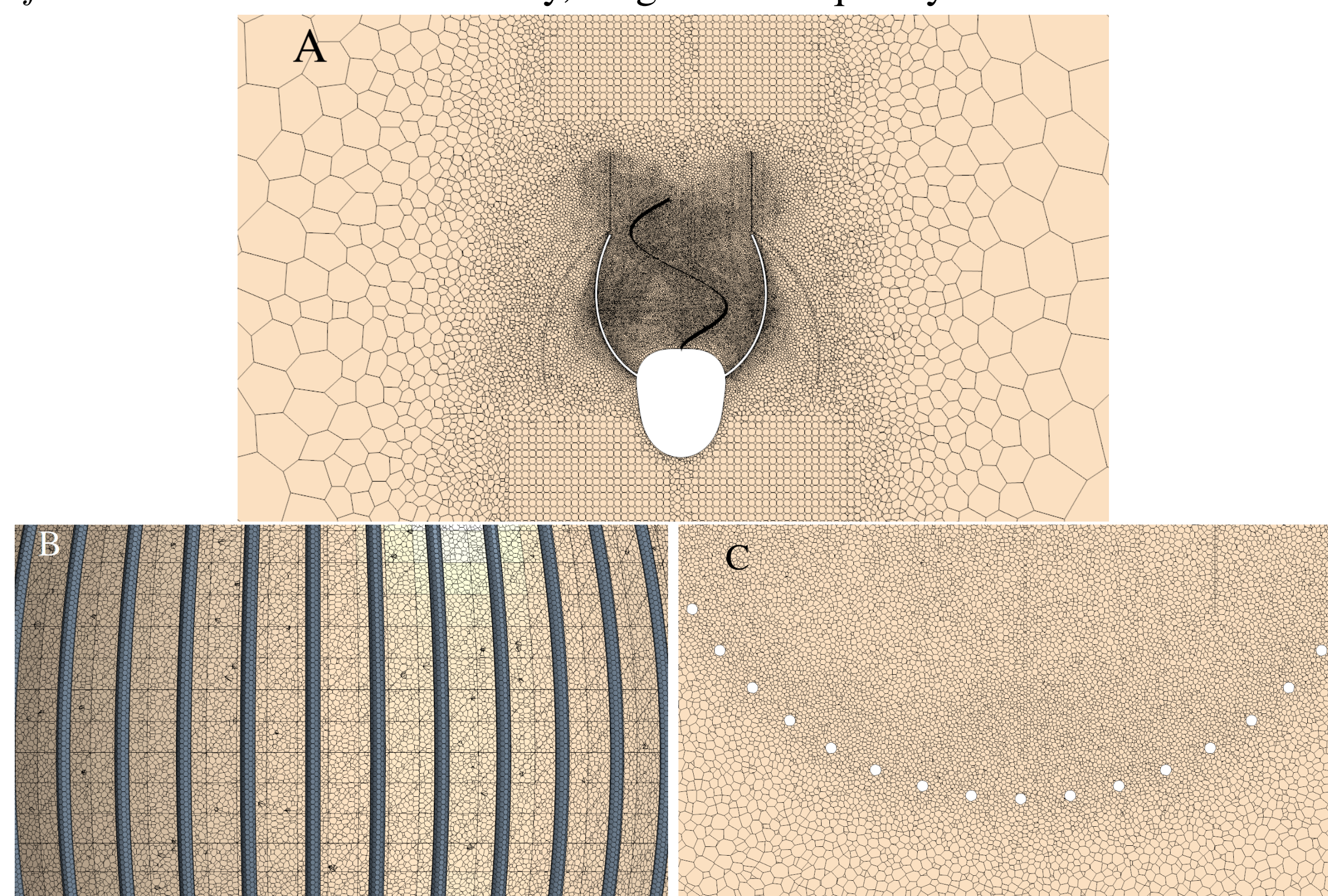
Governing equations and numerical method

Governing equations are the continuity and Navier-Stokes equations:

$$\nabla \cdot u = 0 \quad (1)$$

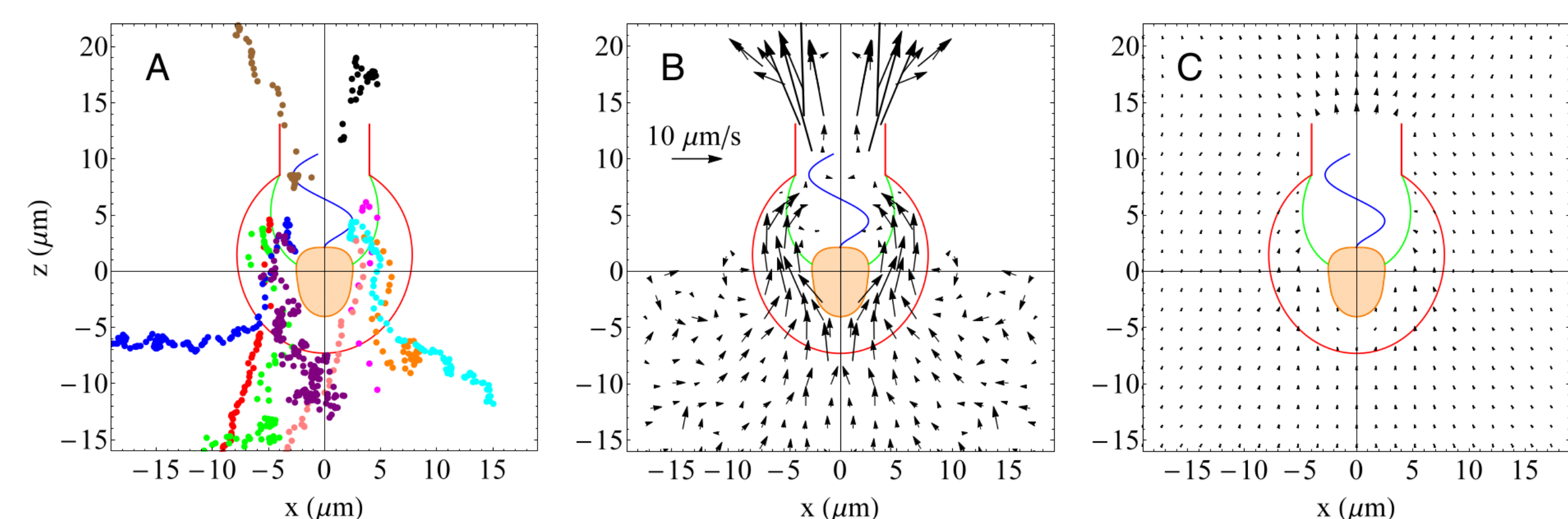
$$\text{Re} \left(\frac{1}{\text{Str}} \frac{\partial u}{\partial t} + (u \cdot \nabla) u \right) = -\nabla p + \nabla^2 u \quad (2)$$

where u and p are dimensionless velocity and pressure, respectively, and $\text{Re} = \frac{\rho U L}{\mu} \approx 0.0007$ is the Reynolds number, and $\text{Str} = \frac{U}{L f} \approx 0.77$ is Strouhal number, where U , L and f are the characteristic velocity, length and frequency.



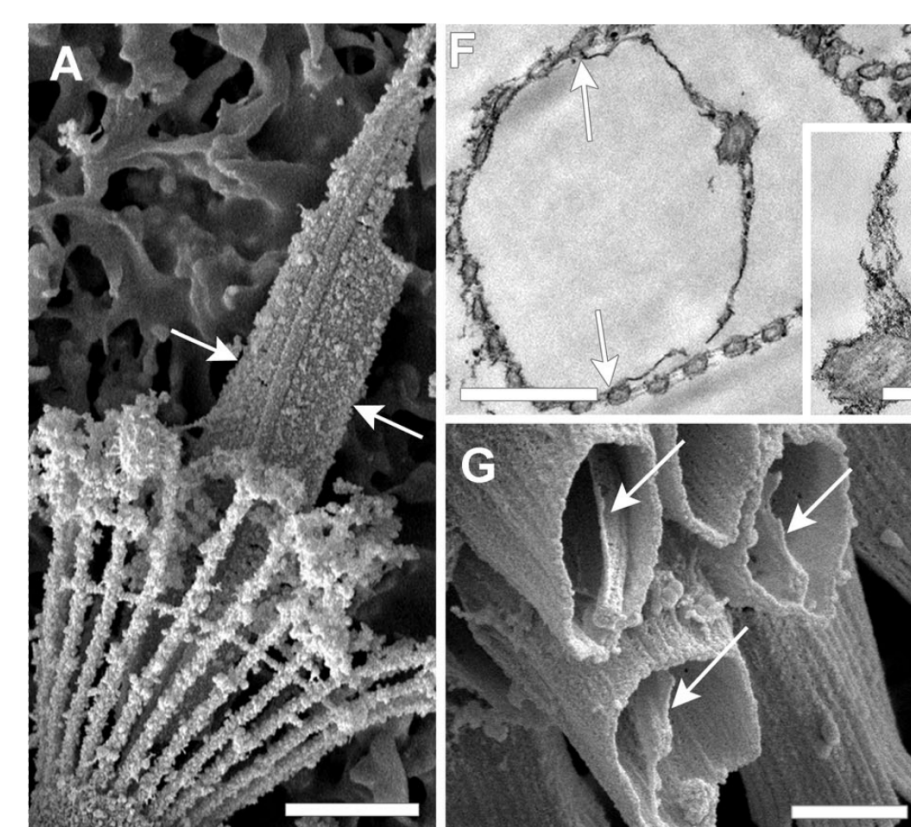
The computational domain is discretized with 4.8 million computational cells. (A) The mesh is chosen very fine around the flagellum and in between the microvilli to resolve the flow structures, whereas a coarse mesh is sufficient to resolve the flow in the far field. (B and C) Details of the mesh between the microvilli seen from the side and in the z direction. (We apply the commercial CFD program STAR-CCM+ version 12.02.010-R8).

Observed versus modelled feeding flow

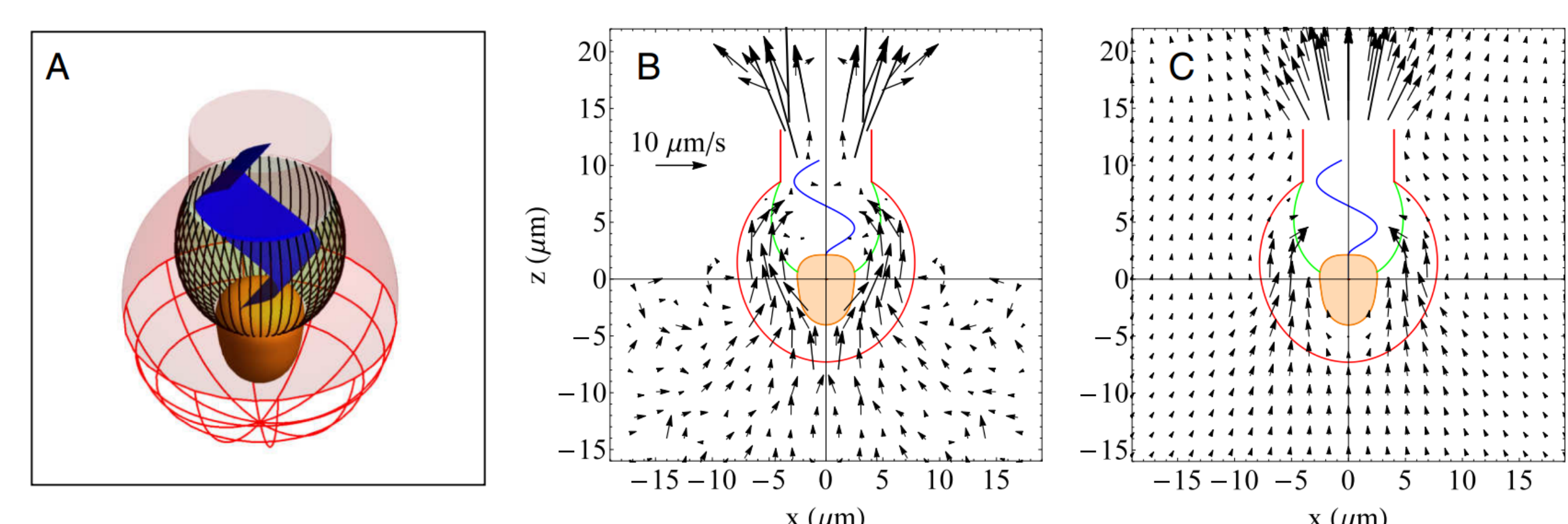


Observed feeding flow and velocity field from CFD model based on the standard description of morphology and flagellum. (A) Representative particle tracks. (B) Average velocity field based on particle tracking. (C) The CFD velocity field in the xz plane is time averaged over the flagellar beat cycle, and the velocity vectors inside filter and chimney are omitted for clarity. The CFD model based on the standard description of morphology and flagellum predicts a feeding flow that is more than an order of magnitude weaker than the experimentally observed flow, and it fails for the observed clearance rate.

CFD model with flagellar vane



A flagellar vane is notoriously difficult to visualize, but sporadically observed in some species of the choanoflagellates. (A) the choanoflagellate *Monosiga brevicollis* (scale bar $2\mu\text{m}$), and (F,G) the choanocyte of the sponge *Spongilla lacustris*. The vane spans the width of the collar. (scale bar $1\mu\text{m}$) [1].



(A) The model morphology shows organism with $5\mu\text{m}$ wide flagellar vane (blue). (B) Observed average velocity field. (C) The CFD velocity field in the xz plane is time averaged over the flagellar beat cycle, and the velocity vectors inside filter and chimney are omitted for clarity. The CFD model with a flagellar vane predicts a feeding flow and a clearance rate in good agreement with the experimental observation.

References

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